‘Bad’ Oil, ‘Worse’ Oil and Carbon Misallocation (joint with F.Henriet and L.Reitzmann)

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- Carbon mispricing: extraction/refining emissions largely ignored; mostly consumption taxes on oil products (e.g., gasoline, diesel) that ignores life-cycle emissions heterogeneity.
- Differences in private extraction cost/barrel: Production inefficiencies partly due to market power (Asker et al., 2019).

This paper:

- quantifies carbon misallocation since 1992 (Rio Summit): $\rightarrow$ extra emissions from "wrong" field-level productions (given aggregate supply).
- identifies the deposits that should have been more exploited, and those less so $\rightarrow$ maps countries' ecological debts.
- disentangles the misallocation in CO_2eq emissions attributable to market power or to the absence of a tax on CO_2eq emissions.
- quantifies gains from carbon pricing of extracting-refining activities in the future.
- examines the distribution of stranded oil deposits as of 2019 taking into account differences in extraction costs and carbon intensities.

To do so:

- we use rich field-level data on deposits' extraction cost, carbon intensity and size (entire World production post 1992).
- we compare the historic supply to counterfactuals that factor in pollution (with the same aggregate-supply path).

Findings' preview: Past Misallocation 1992–2018

Inefficient emissions: at least 11.0GtCO_2eq (aggregate supply unchanged)

- Twice the annual global CO_2eq emissions from transports.
- Cost about US$2.2 trillion (social cost of carbon of $200/t$CO_2$eq).

Ecological debts (1992–2018)

- $\uparrow$ Saudi Arabia, Kuwait; $\downarrow$ Venezuela, Canada, China.
- Kyoto Protocol's Annex B over-extracted oil by 46%.

Carbon Misallocation distinct from Private-Cost Misallocation

- Cost-effective supply (that ignores pollution) brings only 3-10% of the emission reductions of the optimal supply.
- Around 30% of total misallocation attributable to OPEC's market power.
- Around 30% of total misallocation attributable to carbon mispricing.
- The rest is due to other sources of distorsion (e.g. production taxes, political economy forces).

Findings' preview: Looking towards the future

The post-2019 optimal supply structure would save 9.3 $GtCO_2eq$ compared to a cost-effective supply that ignores pollution:

- Keeping the same aggregate supply each year across scenarios;
- Future aggregate supply follows the Net-zero in 2050 pathway (IEA, 2021).

Very unequal distribution of stranded oil reserves.

- Kuwait 22%; Canada 96%.

Policy relevance: Why a supply-side policy?

- Transport sector is difficult to decarbonize: demand reduction is costly (but necessary) $\rightarrow$ Supply-side approach to add.

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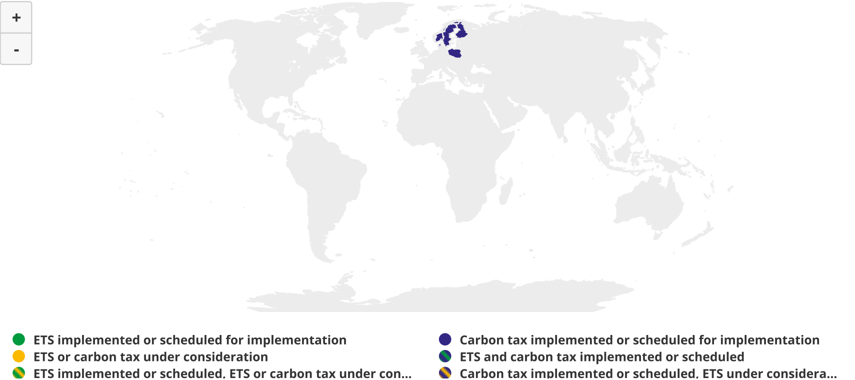
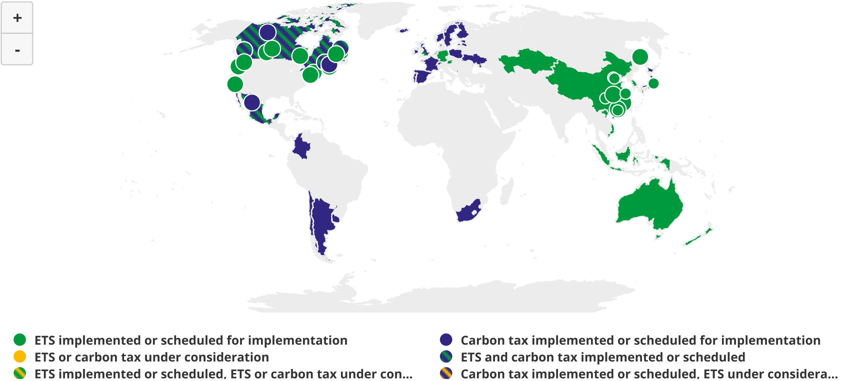
- Transport sector is difficult to decarbonize: demand reduction is costly (but necessary) $\rightarrow$ Supply-side approach to add.
- Still room for such policy as carbon emissions have been mispriced:
  - Differences in CO_2eq emissions/barrel originate from extraction and refining activities.
  - No direct taxation of production emissions in fuel-producing countries.

Carbon pricing as of 1992 (World Bank)



Carbon pricing as of 2023 (World Bank)



- Oil extraction/refining are not often covered by existing carbon prices.
- Carbon prices are often below main estimates of social cost of carbon.

Policy relevance: Why a supply-side policy?

- Transport sector is difficult to decarbonize: demand reduction is costly (but necessary) $\rightarrow$ Supply-side approach to add.
- Still room for such policy as carbon emissions have been mispriced:
  - Differences in CO_2eq emissions/barrel originate from extraction and refining activities.
  - No direct taxation of production emissions in fuel-producing countries
  - Limited actions from consumer countries: they can modify the allocation of refiners and distributors' fuel demand to reduce the carbon footprint of their oil products (see attempts such as the EU Fuel Quality Directive (2009) and California Low Carbon Fuel Standard (2007)).

This paper: Methodology and Data requirements

Methodology to measure gains from supply recomposition:

- Past: We compare deposit-level counterfactual productions and realized productions post 1992 (The Earth Summit).
- Future: We compare deposit-level counterfactual productions and a cost-effective supply that ignores pollution.
- Counterfactuals are constructed by minimizing discounted *social* cost of oil extraction under various feasibility constraints, assuming annual demands are satisfied.

Data we need

- At the deposit level: extraction cost + carbon intensity + past productions + reserves.
- Global annual demands.

Micro-data on oil deposits

Rystad proprietary database: gathers upstream data on all significant oil fields from 1970 through 2018:

- 14,000 oil assets.
- Productions, costs (operational and capital expenditures), field location, ownership.
- Oil and reservoir characteristics (e.g., API gravity, gas-to-oil ratio).
- No carbon intensities.

Estimating CO_2eq intensity (CI) at the field level

2 state-of-the-art datasets/models for CI estimation (Oil-Climate Index).

Production (from exploration to the refinery gate)

- Masnadi et al. (2018): public data of 958 fields, 54% of the world oil production (CI based on OPGEE model).
- Match these fields to those in Rystad.
- Select a reduced-form model to best explain CI with Rystad variables: oil type, gas-to-oil ratio, offshore + other sources: Flaring (satellite data, US NOAA), Steam injection (IEA). ▸ Regression ▸ Table ▸ Fit ▸ Robustness
- We use this model to predict CI for the other fields.

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Refining

- PRELIM model to calculate CI for most common crudes.
- Link crudes to deposits using location, oil type, and firms.
- Select a reduced-form model to best explain CI. ▸ Regression
- We use this model to predict CI for the other fields.

Variance in oil CO_2eq emissions mostly from extraction

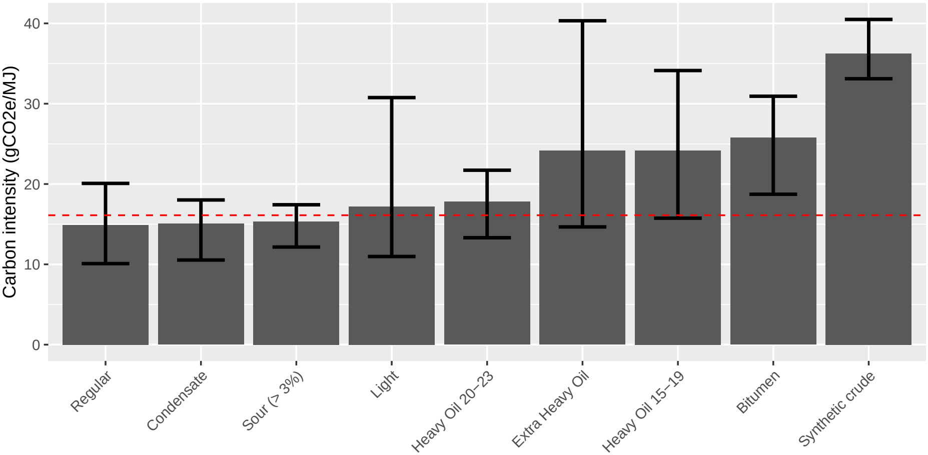
- Extraction: average CI is 10.15 gCO_2eq/MJ.
  25% of the distribution falls under 6.65, 50% under 8.55, and 75% under 10.84.

- Refining: average CI is 5.15 gCO_2eq/MJ.
  25% of the distribution falls under 4.24, 50% under 4.87, and 75% under 5.19.

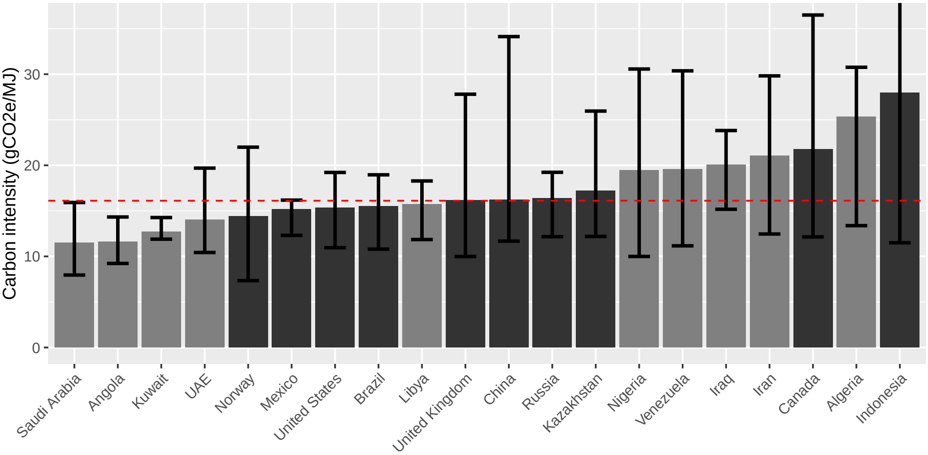
- Combustion: average CI is 76.05 gCO_2eq/MJ $\rightarrow$ oil barrels are homogeneous on the demand side.

Focus on extraction and refining emissions that account to about 17% of the life-cycle emissions of an oil barrel.

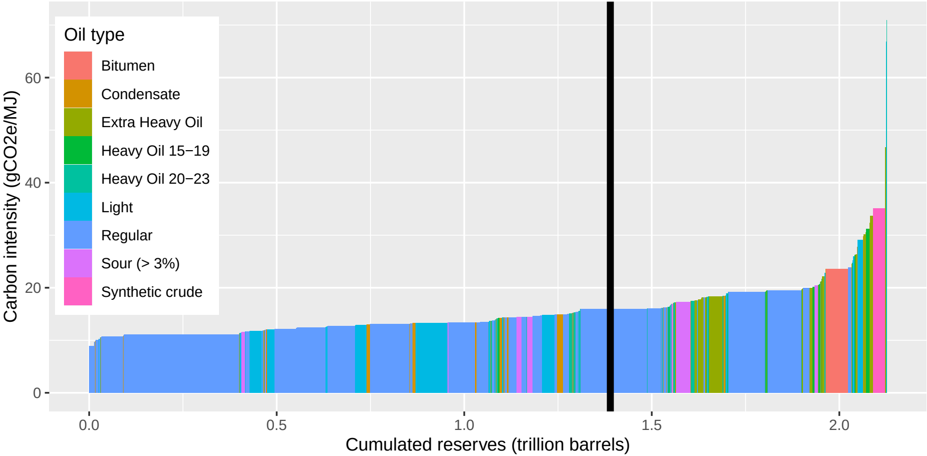
CO_2eq per MJ by oil type (extraction-refining)



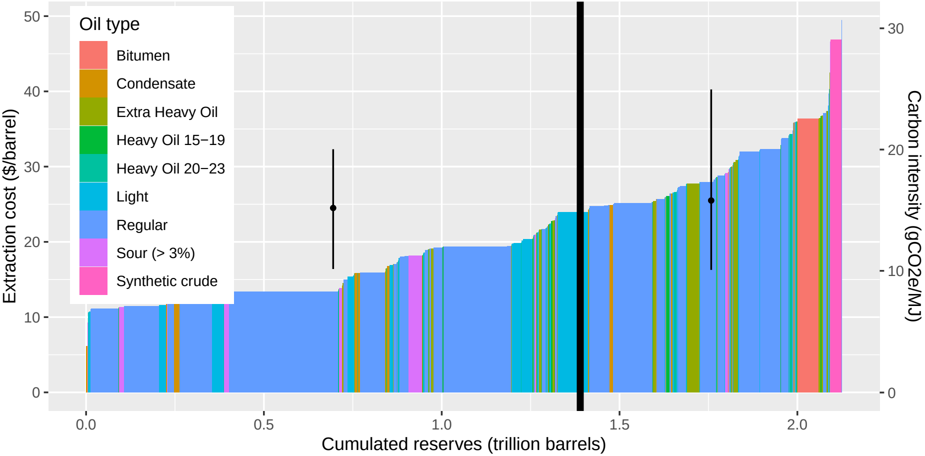
CO_2eq per MJ by country (extraction-refining)



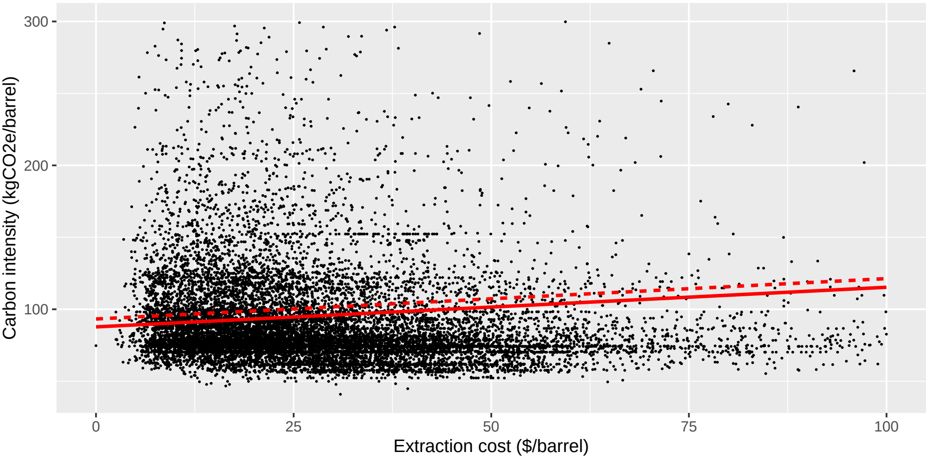
CI-based supply curve (1992 reserves)



Private cost-based supply curve (1992 reserves)



CO_2eq and extraction cost per barrel: low correlation



Measuring misallocation costs

Total misallocation is the gap between the discounted social cost of the optimal counterfactual production and that from the baseline, assuming **identical annual demands** in both scenarios.

Optimal counterfactual production: solution of the **social** cost minimization program:

- aggregate production matched exogenous annual demand;
- feasibility constraint (resource availability, plateau-decline production pattern, limited reserves, cost that increases with depletion)
- carbon cost (\$200/tCO_2eq in 2018) increases as interest rate.

Supply recomposition reduces the social production cost via two channels:

- deposits' cumulative extraction (impact private and env. costs);
- the extraction order (impact only private extraction costs).

Optimal counterfactual production

- μ, carbon cost (\$200/tCO_2eq in 2018)
- θ_d, carbon intensity in field d; c_{dt} private-extraction cost (/barrel)
- x_{dt} production from field d at date t; D_t the World demand
- R_{dt} reserves at time t; $\min(k_d, \alpha_d R_{dt})$ field-extraction capacity at date t.

Optimal production is the solution of:

$$\mathcal{P}_1(T_0, T_f, \mu): \quad \min_{x_{dt}} \sum_{T_0}^{T_f} \sum_d (c_{dt} + \theta_d \mu_t) x_{dt} e^{-r(t-2018)} \text{ s.t.}$$

$$\text{Annual demands:} \quad \sum_d x_{dt} \geq D_t \text{ for all } t \tag{1}$$

$$\text{Reserves:} \quad \sum_{T_0}^{T_f} x_{dt} \leq R_{d,T_0} \text{ for all } d \tag{2}$$

$$\text{Extractive capacities:} \quad 0 \leq x_{dt} \leq k_d \text{ for all } t, d \tag{3}$$

$$\text{Extractive capacities:} \quad x_{dt} \leq \alpha_d R_{dt} \text{ for all } t, d \tag{4}$$

$$\text{Resource availability:} \quad x_{dt} = 0 \text{ for all } d, t < t_d \tag{5}$$

$$\text{Stock effect:} \quad c_{dt} = f\left(\frac{R_{d,T_0} - R_{d,t}}{R_d}\right) \text{ for all } t, d \tag{6}$$

$$\text{Social cost of carbon:} \quad \mu_t = \mu e^{r(t-2018)} \text{ for all } t \tag{7}$$

Misallocation costs = Gains from Supply recomposition

Carbon and private cost misallocations = gap between the discounted total cost of the optimal counterfactual production and that from the baseline, assuming **identical annual demands** in both scenarios.

$\tilde{x}_{dt}$: baseline production of field d in year t; $\tilde{c}_{dt}$ marg. private extraction cost. $\mathcal{MC}$ is the misallocation cost saved by the counterfactual extraction path (x_{dt}), between T_0 and T_f:

$$\mathcal{MC} : ((\mu_t), (x_{dt}), T_0, T_f) \rightarrow$$

$$\sum_{T_0}^{T_f} \sum_{d} (c_{dt} + \theta_d \mu_t) \tilde{x}_{dt} e^{-r(t-2018)} - \sum_{T_0}^{T_f} \sum_{d} (c_{dt} + \theta_d \mu_t) x_{dt} e^{-r(t-2018)}$$

Supply recomposition reduces the social production cost via two channels:

- changes in deposit cumulative extraction (impact private and env. costs);
- the extraction order (impact only private extraction costs).

Optimal counterfactual production

Opportunity costs and finite nature of oil deposits

- We could compare optimal production and observed production in the past (for instance years 1992–2018)...
- but this would over-estimate the gains from optimal production!
- Barrels used before 2018 are no longer available in the future.

Need a future to account for these opportunity costs, $T_f = 2060$

- Exogenous demand post 2018 follows the *Net-zero in 2050* pathway (IEA, 2021).
- Optimal supply post-2018 (with carbon pricing).
- Compare (observed + optimal future) to the optimal counterfactual over *the whole extraction path* which is 1992–2060.

Gains from starting (optimal) supply recomposition in 1992 (instead of 2019)

- Past Misallocation at least 11.0GtCO_2eq; robust to social cost of carbon in the \$50–400/tCO_2eq range. Graph
- Min. private costs generates only 3% of optimal abatement Graph $\rightarrow$ Carbon misallocation and private-cost inefficiency are distinct.

	CO_2eq decrease (GtCO_2eq)	Environmental gains (trillion US\$)	Private gains (trillion US\$)	Total gains (trillion US\$)
Optimum	11.00	2.20	3.70	5.90
Minimal private costs	0.32	0.06	4.18	4.24

Production changes in the Top-15 producing countries

	Observed production 1992–2018 (% of global production)	Change in production 1992–2018 (% of 1992–2018 baseline production)	
		Optimum (past)	Min. private costs (past
Saudi Arabia	13.7	131.4	63.0
Russia	11.5	-9.0	8.1
US	9.7	-58.2	-55.5
Iran	5.3	32.3	73.5
China	5.0	-88.8	-87.0
Mexico	4.2	-28.5	-20.6
UAE	3.7	91.5	44.4
Canada	3.5	-77.5	-75.0
Venezuela	3.5	-58.2	-23.3
Iraq	3.2	186.1	276.6
Norway	3.2	-61.3	-65.8
Kuwait	3.0	142.2	144.0
Nigeria	3.0	-63.9	-43.9
UK	2.3	-97.1	-89.2
Brazil	2.2	-96.9	-92.4
OPEC	43.2	60.5	54.2
Annex B	31.8	-45.9	-39.2
Non Annex B	68.2	21.4	18.3

Constraining country-level productions in the past 1/2

- Supply recomposition $\rightarrow$ significant production variation across countries
- International transfers and compensations are difficult!
- Minimize the social cost of oil extraction under feasibility constraints:
  1. Annual productions in each OPEC country match baseline's ones. ▸ Table
  2. Annual productions in each country match baseline's ones. ▸ Table
- **Still large emission reductions: 9–11GtCO_2eq**.
- This argues in favor of political feasibility of supply recomposition.

Constraining country-level productions in the past 2/2

- **Private economic gains from supply recomposition are considerably reduced**.
- Considering existing distorsive production taxes (adding royalties and other production taxes to private costs when constructing counterfactuals) further reduces the private gains from supply recomposition, but leaves emission reduction barely unchanged at 8.1GtCO_2eq.
- Private cost misallocation is largely explained by market power, country-level distortions such as preferences for domestic production and existing production taxes.

Future: Gains from starting supply recomposition in 2019

Significant emission gains post 2018 (not changing the past) compared to a cost-effective supply that ignores CI heterogeneity of oil barrels: 9.3GtCO_2eq.

	CO_2eq decrease ($GtCO_2$eq)	Env.gains (trillion US$)	Private gains (trillion US$)	Total gains (trillion US$)
Clean future (Net-zero 2050)	9.30	1.86	-0.62	1.24
Clean future (Strict-zero 2050)	6.22	1.24	-0.41	0.83
Clean future (APS)	7.17	1.43	-0.45	0.99

- *Net-zero 2050*: the demand follows the net zero pathway of IEA (2021), assuming the demand reaches zero in 2060.
- *Strict-zero 2050*: the demand falls linearly from 2018 to reach zero in 2050.
- *Announced Pledges Scenario (APS)*: the demand is coherent with current decarbonation pledges of countries.

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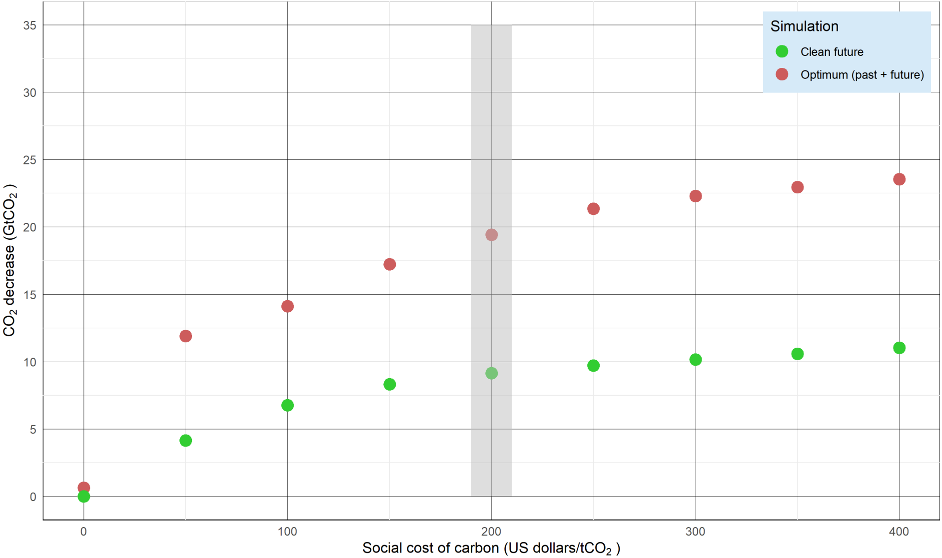
The greater the demand the larger are the gains (Strict-zero to Net-zero), but there is a limit to that: if all oil barrels are exhausted no more possible to select good barrels...(from Net-zero to APS)

Countries' stranded reserves (% of 2019 reserves)

	Net-zero in 2050		Strict zero in 2050		APS	
	Clean	Cost-effective	Clean	Cost-effective	Clean	Cost-effective
Saudi Arabia	21.8	23.0	35.7	43.4	14.3	14.5
Russia	52.8	46.8	73.1	72.5	20.3	16.5
US	56.0	66.1	86.4	96.5	21.1	25.1
Iran	56.6	25.1	69.6	48.5	22.0	14.9
China	84.1	89.9	93.8	96.6	35.1	46.1
Mexico	57.3	77.7	83.7	84.7	23.1	26.7
UAE	23.0	31.0	40.2	45.3	14.5	15.0
Canada	95.7	95.8	97.6	99.5	61.1	47.1
Venezuela	89.0	87.9	91.5	91.8	34.0	29.2
Iraq	56.4	24.3	70.9	41.2	20.1	15.7
Norway	43.6	73.7	62.8	91.9	20.8	30.4
Kuwait	22.4	21.4	34.9	35.0	13.9	14.0
Nigeria	82.8	87.8	89.0	92.0	29.1	40.0
UK	87.0	98.6	98.2	99.2	29.8	54.8
Brazil	76.8	99.9	97.8	99.9	27.9	39.7
OPEC	40.6	33.0	54.0	50.1	18.4	17.0
Annex B	64.0	68.2	84.0	89.7	29.7	28.4
Non Annex B	47.3	45.4	62.2	59.6	20.5	21.1
Global	52.5	52.5	69.0	69.0	23.4	23.4

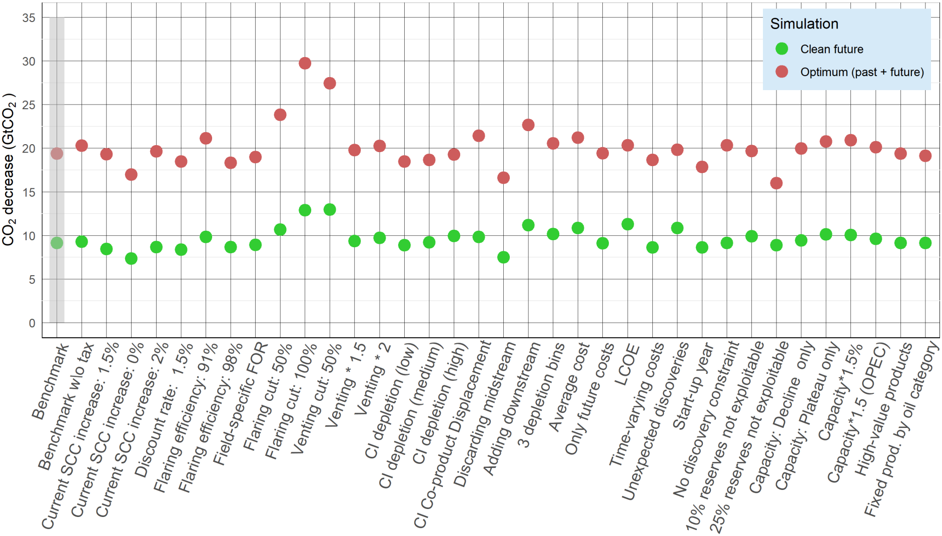
Sensitivity analysis: the social cost of carbon



Sensitivity analysis: others

- ✓ Discounted social cost of carbon that decreases through time.
- ✓ Discount rate at 1.5% (instead of 3%).
- ✓ Changes in the extractive-capacity constraint.
- ✓ Changes in the constraint on the year reserves are available: field discoveries over 1992–2018 as surprises.
- ✓ Changes in recoverable reserves' definition (drop 10, or 25%).
- ✓ Alternative CI measures: account for gas production; flaring/venting decrease; CI varying with depletion; various scopes (add combustion or discard refining).
- ✓ Alternative private extraction cost measures: average cost; average costs with only post-1992 costs; time-varying costs; LCOE.
- ✓ Imperfect substitution between oil deposits: production of high-value oil products cannot decrease; fixed productions of light + regular.

Sensitivity analysis: others



Policy implications & Implementation

This paper informs the debate on climate-change mitigation costs.

1. Any regulation of oil use that treats all crudes similarly misses out on large mitigation opportunities.
   - Cost of relying *only* on demand reduction.
2. Still large gains from supply recomposition now and in the future.
3. Environmental policy $\neq$ pro-competition policy.

Ingredients for implementation:

- Need carbon pricing in the oil industry!
- Distributional impacts make acceptance uneasy.
- Fixing country productions and recomposing supply yields large gains.
  - Production quotas by regions + within-region carbon prices.
- Non-cooperative countries? Approach *à la* Harstad (2012): Buying all bitumen, extra-heavy or heavy oils deposits, and those with extreme flaring-to-oil ratios (top 21%) in 1992, then cost-effective supply.

Conclusion

- Large emission reductions (20.3GtCO_2eq) from supply recomposition over the 1992–2060 period (unchanged aggregate supply).
- Robust to various changes in assumption about productions constraints, cost and carbon intensity estimates.
- Carbon misallocation distinct from private cost inefficiency, but the costs of these misallocations are of similar magnitude.
- Evidence of large "ecological debts" of dirty-oil owners.
- Large production reallocation between countries.
- Still large gains even with constrained country productions.

Thank you for your attention!

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Appendix

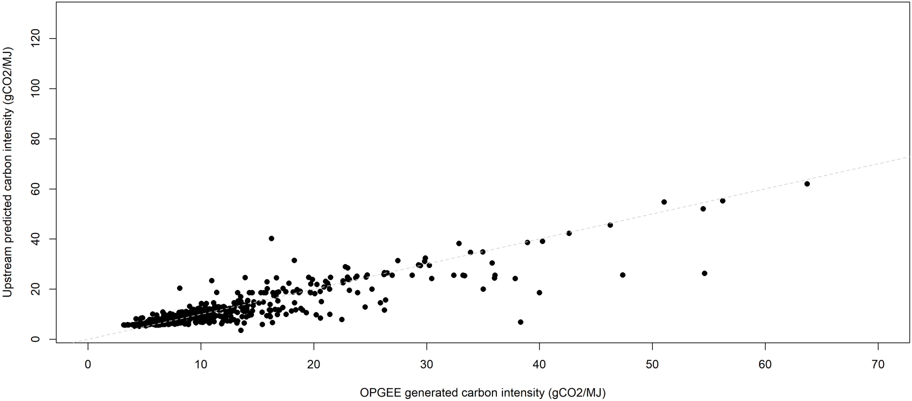
Limiting production changes at the country level ◂ Back

	(1) OPEC annual joint productions fixed			
	CO_2eq decrease ($GtCO_2$eq)	Environmental gains (trillion US$)	Private gains (trillion US$)	Total gains (trillion US$)
Optimum	10.73	2.15	2.85	5.00
Min. private costs	-0.20	-0.04	3.26	3.22
	(2) Country annual productions fixed			
	CO_2eq decrease ($GtCO_2$eq)	Environmental gains (trillion US$)	Private gains (trillion US$)	Total gains (trillion US$)
Optimum	8.50	1.70	1.56	3.26
Min. private costs	-0.07	-0.01	2.04	2.03
	(3) Country annual productions fixed: maintaining production taxes			
	CO_2eq decrease ($GtCO_2$eq)	Environmental gains (trillion US$)	Private gains (trillion US$)	Total gains (trillion US$)
Optimum	8.17	1.63	- 0.28	1.35
Min. private costs	0.41	0.08	0.17	0.25

Carbon pricing in the 10 largest oil producers as of 2018

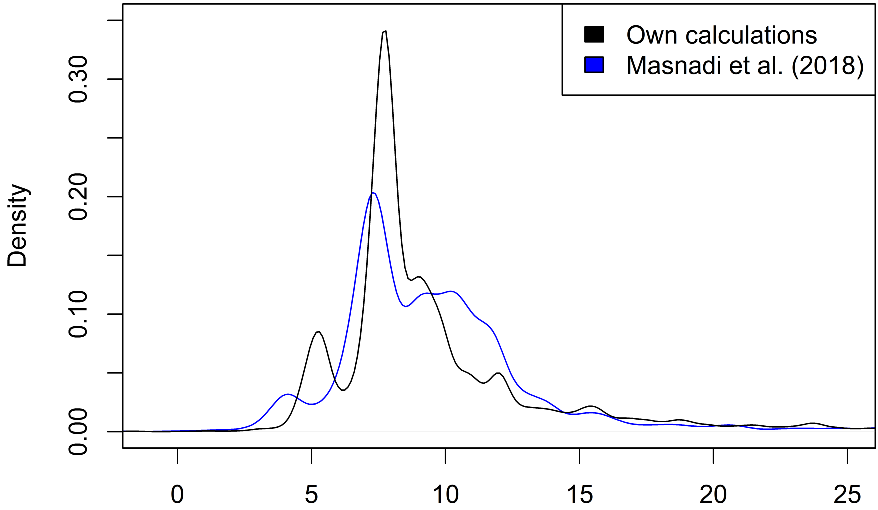
Country	Share world supply	Year start–end	Sectors
US ETS	18%		
RGGI		2009-	power
Washington		2017-	industry, power, transport, waste, buildings
Massachusetts		2018-	power
California		2012-	power, road fuel distribution
Canada	5%		
Alberta		2007-17	industry, power
Alberta CCIR		2018-	industry, power, large oil-sands mines
Quebec ETS		2013-	power, industry, distribution, fossil-fuel imports
BC tax		2008-	all except agriculture (from 2013)
Ontario CaT		2017-19	all except agriculture, waste, aviation, sea transport
China ETS	5%		
Shanghai		2013-	power, petrochemicals, aviation, heavy industry
Shenzhen		2013-	power, manufacturing
Tianjin		2013-	petrochemicals, power, oil & gas, heavy industry
Guangdong		2013-	power, cement, steel, petrochemicals
Chongqing		2014-	power, heavy industry
Hubei		2014-	power, heavy industry, petrochemicals
Beijing		2013-	power, heavy industry, petrochemicals

Correlation: predicted and OPGEE-calculated upstream carbon intensities ◂ Back



Predicted vs OPGEE-calculated CIs: 2015 upstream

◂ Back



Upstream carbon-intensity estimation

Back

	Energy-Based Allocation	Co-Product Displacement
Synthetic	25.584***	25.706***
	(1.218)	(1.273)
Bitumen	4.017***	4.704***
	(1.005)	(1.05)
Condensate	7.687***	7.387***
	(0.956)	(0.999)
Extra Heavy	9.899***	9.776***
	(0.628)	(0.657)
Heavy (15-19)	8.848***	8.962***
	(0.759)	(0.794)
Heavy (20-23)	7.403***	7.464***
	(0.608)	(0.635)
Light	7.359***	7.261***
	(0.384)	(0.402)
Regular	7.701***	7.751***
	(0.223)	(0.233)
Sour ($>$ 3%)	7.689***	7.985***
	(1.056)	(1.104)
Offshore	-2.07***	-2.383***
	(0.245)	(0.256)
Steam Injection	14.593***	13.979***
	(0.782)	(0.817)
Major	-0.418	-0.56**
	(0.266)	(0.278)
GOR (kscf/bbl)	0.111	-0.098
	(0.071)	(0.074)
FOR (kscf/bbl)	12.739***	13.454***
	(0.156)	(0.163)
R-squared	0.949	0.945
Adjusted R-squared	0.948	0.944

Estimating extraction-refining carbon intensities ◂ Back

The selected models are:

Upstream

$$
\begin{aligned}
CI_f^{OPGEE,C} &= \textstyle\sum_0^8 \beta_i^C OilType_{i,f} + \beta_9^C GOR_f + \beta_{10}^C FOR_f \\
&+\beta_{11}^C SteamInjection_f + \beta_{12}^C Offshore_f + \beta_{13}^C Major_f + \epsilon_f ,
\end{aligned}
$$

Midstream

$$
\begin{aligned}
CI_f^{PRELIM} &= \beta_0 + \beta_1 API_f + \beta_2 API_f^2 + \beta_3 API_f^3 + \beta_4 API_f^4 \\
&+\beta_5 Sour_f + \beta_6 Major_f + \epsilon_f ,
\end{aligned}
$$

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